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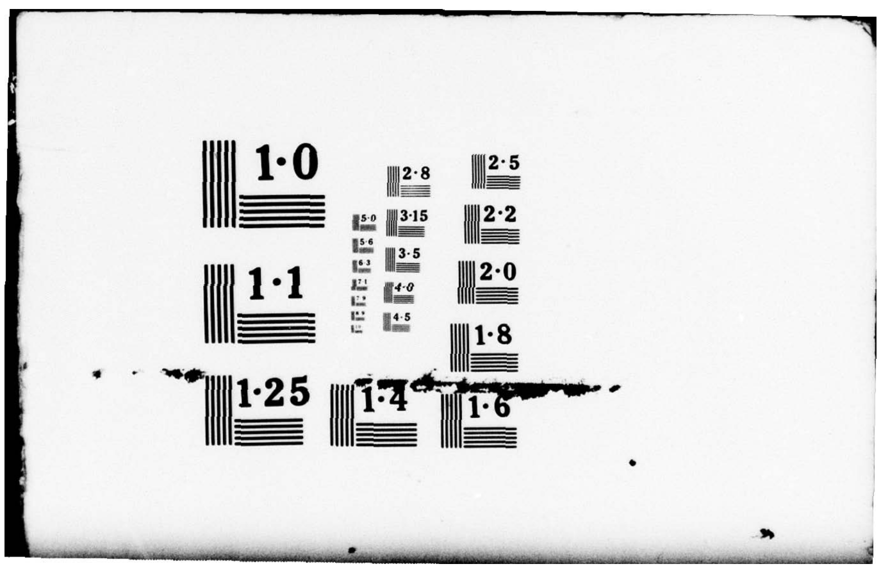
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USING LOGARITHMIC CHARACTERISTICS TO CALCULATE BROAD-BAND MATCHING OF A GENERATOR WITH A LOAD

by

Yu. Ya. Yurov and V. A. Nelep

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В в	*В в*	V, v	Т т	*Т т*	T, t
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Д д	*Д д*	D, d	Ф ф	*Ф ф*	F, f
Е е	*Е е*	Ye, ye; E, e*	Х х	*Х х*	Kh, kh
Ж ж	*Ж ж*	Zh, zh	Ц ц	*Ц ц*	Ts, ts
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О о	*О о*	O, o	Ю ю	*Ю ю*	Yu, yu
П п	*П п*	P, p	Я я	*Я я*	Ya, ya

*<u>ye</u> initially, after vowels, and after ъ, ь; <u>e</u> elsewhere. When written as ё in Russian, transliterate as yё or ё. The use of diacritical marks is preferred, but such marks may be omitted when expediency dictates.

GREEK ALPHABET

Alpha	Α	α	α	Nu	Ν	ν	
Beta	Β	β		Xi	Ξ	ξ	
Gamma	Γ	γ		Omicron	Ο	ο	
Delta	Δ	δ		Pi	Π	π	
Epsilon	Ε	ε	ϵ	Rho	Ρ	ρ	ϱ
Zeta	Ζ	ζ		Sigma	Σ	σ	ς
Eta	Η	η		Tau	Τ	τ	
Theta	Θ	θ	ϑ	Upsilon	Τ	υ	
Iota	Ι	ι		Phi	Φ	φ	ϕ
Kappa	Κ	ϰ	κ ϰ	Chi	Χ	χ	
Lambda	Λ	λ		Psi	Ψ	ψ	
Mu	Μ	μ		Omega	Ω	ω	

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RUSSIAN AND ENGLISH TRIGONOMETRIC FUNCTIONS

Russian	English
sin	sin
cos	cos
tg	tan
ctg	cot
sec	sec
cosec	csc
sh	sinh
ch	cosh
th	tanh
cth	coth
sch	sech
csch	csch
arc sin	$\sin^{-1}$
arc cos	$\cos^{-1}$
arc tg	$\tan^{-1}$
arc ctg	$\cot^{-1}$
arc sec	$\sec^{-1}$
arc cosec	$\csc^{-1}$
arc sh	$\sinh^{-1}$
arc ch	$\cosh^{-1}$
arc th	$\tanh^{-1}$
arc cth	$\coth^{-1}$
arc sch	sech^{-1}
arc csch	csch^{-1}

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rot	curl
lg	log

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USING LOGARITHMIC CHARACTERISTICS TO CALCULATE BROAD-BAND MATCHING OF A GENERATOR WITH A LOAD

Yu. Ya. Yurov and V. A. Nelep

Summary

This report gives a procedure for finding the analytical expression for the frequency dependence of the input impedance of a matching quadrupole loaded by the generator impedance when powered from the side of the load. This frequency function can be given graphically or analytically. Its analytical expression is obtained in standard form convient for synthesizing a matching quadrupole by using its logarithmic characteristics. The necessary and sufficient condition of the realizability of this impedance in the form of a

passive two-terminal network with lumped parameters is established. This method is used to determine the parameters of a matching quadrupole with a passive load.

Introduction

Broad-band matching of a generator to a load (Fig. 1) which has a resistance frequency dependence is a complex problem. Lengthy computations must be made to determine the parameters of the matching quadrupole by the existing procedures [1-6]. The engineering calculation formulae have only been obtained for loads which can be represented accurately enough by a circuit with lumped parameters containing a maximum of two reactive elements. In these broad-band matching methods, all the functions are considered depending on the complex variable $p = \sigma + i\omega$, and the Chebyshev or Butterworth polynomials are used to approximate the power transfer coefficient. The first condition robs the calculation of its clarity, making it necessary to perform it with excessive accuracy. The second condition complicates the matching quadrupole circuit, since additional conditions which are not usually necessary are imposed on the zero position and the poles of the power transfer coefficient.

In this report, all the functions are considered depending on

the imaginary part of the complex variable, i.e., on the real frequency. We can show (7) that in this case, extremely approximate methods, e.g., graphic, can be used to calculate the parameters of the matching quadrupole which do not require the use of the Chebyshev or Butterworth polynomials. A method of determining the parameters of the matching quadrupole using logarithmic characteristics is proposed. This method makes it possible to considerably reduce the volume of computations and calculate matching for any passive load.

The dependence of the power transfer coefficient on the load and matching quadrupole parameters is [2]:

$$G=1-\left|\frac{Z_2-z_H^*}{Z_2+z_H}\right|^2, \qquad (1)$$

where G is the power transfer coefficient; z_H, z_H^* are the resistance and complex-coupled load impedance; Z_2 is the input impedance of the matching quadrupole from the load, when its input clips are closed on the internal generator impedance (Fig. 1).

We will designate the ratio of amplitudes $|Z_2|/|z_H|$ by ε and we will rewrite (1) as follows:

$$G=\frac{4\varepsilon\cos\varphi_2\cos\varphi_H}{1+2\varepsilon\cos(\varphi_2-\varphi_H)+\varepsilon^2}, \qquad (2)$$

where φ_2, φ_H are the phase angles of impedances Z_2 and z_H.

Phase angles ϕ_2 and ϕ_H are completely symmetrical in (2) and the value of G does not vary if we substitute ε^{-1} for ε in (2). Furthermore, the majority of the values of G lie within 0.6-1. Therefore, the curves of dependence $\varphi_H = f(\varphi_2)$ are given in Fig. 2 at ε = const and G = 0.6; 0.8; 1. The curves are easily calculated if the axis of coordinates ϕ_2 and ϕ_H are turned to a 45° angle. Angles ϕ_2 and ϕ_H change within the limits $(-\pi/2;\ \pi/2)$, since the load and the matching quadrupole are passive. In Fig. 2, $\varphi_H \geqslant 0$; it is obvious that the curves remain the same if we reverse the signs both on the x- and y-axis.

The curves which were plotted make it possible to find G at a given Z_2 or, assigning G, to find the range of permissible values of the amplitude and phase of Z_2 for any load impedance.

For example, if $\varepsilon = 3\ dB,\ \varphi_H = 60°,\ \varphi_2 = -40°$, then G $\cong$ 0.82; if G $\geqslant$ 0.8, ϕ_H = 60°, then $-72° \leqslant \varphi_2 \leqslant -27°$ and -3 dB $\leqslant$ ε $\leqslant$ 3 dB.

This report considers a matching quadrupole with lumped parameters; therefore, $Z_2(p)$ must be a rational positive real function (PRF) [8]. It follows from the properties of a PRF that it can always be represented by the product of the factors

$T, (Tp)^{\pm 1}, (Tp+1)^{\pm 1}, (T^2p^2+2\xi Tp+1)^{\pm 1}$ (here and below T, ξ are positive real numbers, $0 \leqslant \xi < 1$). In the appendix it is proven that inequalities $\frac{\pi}{2} \leqslant \varphi_2 \leqslant \frac{\pi}{2}$ are not only necessary, but also sufficient conditions for the positiveness and reality of function $Z_2(p)$, represented in the form of the product of these factors.

The determination of an analytical expression for function Z_2 which satisfies the necessary and sufficient conditions of positiveness and reality and for which the amplitude and phase are within the range of permissible values is the main purpose of this study.

This method can also be used to calculate matching in the SHF range if we find the equivalent matching quadrupole in the form of a circuit with distributed parameters.

Finding the Analytical Expression for Z_2 Using Logarithmic Characteristics

The logarithmic amplitude and phase characteristics (LKh) proposed by Bode [9] are the curves of the amplitude in decibels and phase in degrees of the frequency function plotted depending on log ω. We will list the LKh properties which will be used later [10].

The amplitude characteristic $(Ti\omega)^{-1}$ is a straight line with slope of -6 dB per octave, while the phase characteristic is straight line $\phi = -90°$. **The amplitude** characteristics $(Ti\omega+1)^{-1}$ (broken lines) and $[(Ti\omega)^2+2\xi Ti\omega+1]^{-1}$, **shown** in Fig. 3., have asymptotes. One asymptote is the x-axis, and the other is a straight line with a slope of -6 dB **per octave** for $(Ti\omega+1)^{-1}$ and -12 dB per octave for $[(Ti\omega)^2+2\xi Ti\omega+1]^{-1}$. **The asy**mptotes intersect each other at point ω = **1/T from the abscissa. The** LKh of the inverses of the functions under consideration, which are shown in Fig. 3, are symmetrical to the x-axis of the LKh. Multiplication is replaced by the addition of the LKh; therefore, it is easy to find the curves of the complex function which consists of multiplying the factors in question. The properties of the LKh make it possible to plot the curves of the dependence of the amplitude and phase of Z_2 on frequency so that they satisfy the above conditions, as well as to find the analytical expression for Z_2 from the curves obtained.

This problem is solved in three steps (Fig. 4, which shows an example of calculating matching, can be used as an illustration).

1. The amplitude is plotted in decibels and the phase in degrees of the normalized load impedance depending on log ω. Given the

transfer coefficient G equal to 0.6 or 0.8, we will select the contour ε = const in Fig. 2 so that the permissible limits of the change in ϕ_2 are sufficiently great. The boundary values of ϕ_2 are plotted on the phase curve, while ε and $-\varepsilon$ in decibels are added to amplitude $|z_n|$. If we do this at the row of points on the frequency axis, we obtain the range of permissible values of the amplitude and phase of Z_2.

We should not assign a large G, since the ranges of permissible values play a secondary role in the calculation and are only used to estimate the value of the transfer coefficient. The broader the matching band and the greater the limits of the change in the amplitude and phase of the load impedance, the smaller the value of G which must be selected.

2. The ranges of permissible values obtained are analyzed by comparing them with the LKh of standard factors (Fig. 3). Then, beginning with the simplest functions (consisting of constant factor T from linear factor $(Ti\omega+1)$ in the numerator or denominator of Z_2, etc.), the asymptotic curve of the amplitude of Z_2 is plotted within the corresponding range. Possible deviations of the precise curves from the asymptota in Fig. 3 are considered here. Beginning with zero, the slope of the asymptote has a factor of 6 dB per octave. In order to make the corresponding asymptotic curve of the phase

characteristic fall in the range of permissible values of ϕ_2, it is necessary to consider the following: if the asymptote has a zero slope, the phase in this section approaches zero if the slope of the asymptote is equal to ± 6 n dB per octave (n = 1, 2, 3, ...), and the phase characteristic approaches ± 90 n°. Furthermore, the longer the asymptote, the closer the phase characteristic is to these values (Fig. 3). At high and low frequencies, i.e., at $\omega \to \infty$ and $\omega \to 0$, the slope of the asymptote should be 0 dB per octave or ± 6 dB per octave, since $\frac{\pi}{2} \leqslant \varphi_2 \leqslant \frac{\pi}{2}$.

It should be pointed out that: a) if the amplitude and (or) phase of Z_2 is inside the range of permissible values, the transfer coefficient will be greater than on the boundaries of the range; b) if the amplitude of $|Z_2|$ turns out to be outside the range of permissible values, the decrease in the transfer coefficient can be compensated for within certain limits by the appropriate selection of ϕ_2, and vice versa (Fig. 2).

The precise curves of the amplitude and phase of Z_2 are plotted and the points of intersection of the asymptote and coefficient ε of the quadratic factors are refined from the asymptotic curve. The phase of each factor is plotted without consideration of sign (Fig. 3 can be used as model in this case), and is designated by a "+" sign for a factor in the numerator and a "-" sign in the denominator. This

facilitates the process of determining the resulting phase and checking to see that inequality $\frac{\pi}{2} < \varphi_2 < \frac{\pi}{2}$ is satisfied throughout the frequency range. Corrections in the asymptotic curve are determined from Fig. 3 and are plotted on the upper part of the calculated curve in accordance with the points of intersection of the asymptotes, then they are added and plotted from the asymptotic curve.

The frequency dependence of G for assigned Z_2 and z_H is plotted using the curves in Fig. 2. When necessary, Z_2 is corrected by introducing a constant factor, displacing the curves along the x-axis, or selecting new values of coefficients T, ξ.

If the matching band is narrow enough and it is inconvenient to use asymptotes, the curves of standard factors (Fig. 3) are combined with the calculated curve and factors are selected directly to make the resultant LKh fall in the range of permissible values and the phase satisfy inequalities $\frac{\pi}{2} < \varphi_2 < \frac{\pi}{2}$.

It may be necessary to plot two or three versions of the curves of the function of Z_2 from the simplest to more complex in order to determine how the frequency dependence of the transfer coefficient changes when Z_2 is complicated. Then the function which best satisfies the conditions of the problem is selected from the

available functions of Z_2.

3. $T_i = 1/\omega_i$ are determined from the abscissas of the points of intersection of asympote ω_i and the analytical expression for $Z_2(p)$ is written, by which a two-terminal network consisting of a reactive (in this case, matching) quadrupole loaded by effective resistance is realized [8, 11]. If the effective resistance is not equal to the internal impedance of the generator, the matching transformer is activated.

We will consider an example which illustrates the use of this method.

Example. Calculate a matching generator with a load in the frequency band $0.6 \leqslant \omega \leqslant 4$. Figure 4 shows the load circuit and its normalized impedance, measured on a mock-up (normalization condition $R_r = 1$).

Since the matching band is broad enough and the frequency dependence of the load impedance is complex, we will set G = 0.6 and we will plot the range of permissible values of Z_2 (dot-dashed lines).

Analyzing this region, we can conclude that amplitude $|Z_0|$ can

be virtually constant in the matching band, while phase ϕ_2 should be close to zero at low frequencies and negative at high frequencies.

Function Z_2 = 3.09 (9.8 dB) falls in the range of permissible values of the amplitude. The phase is equal to zero throughout the frequency range. The corresponding transfer coefficient is shown by the dot-dashed line in Fig. 4.

In order to raise the transfer coefficient at high frequencies, phase ϕ_2 must be made negative in this region. To do this, we make Z_2 more complex by adding the curve of the asymptote amplitude drawn at an angle of -6 dB per octave. The asymptotes intersect the abscissa at point $\omega = 6$. If $\omega > 6$, the phase in the matching band will not differ greatly from zero, and the transfer function virtually does not change. If $\omega < 6$, the matching band obtained is narrow, since the amplitude and phase of Z_2' turn out to be beyond the range of permissible values at high frequencies. The broken line in Fig. 4 shows the amplitude and phase of Z_2', as well as the frequency dependence of the transfer coefficient.

We can plot the curves of a more complex function of Z_2'', consisting of a linear factor in the numerator and a quadratic factor in the **denominator, for example.** Coefficients T and ξ are selected so that $\frac{\pi}{2} < \varphi_2 < \frac{\pi}{2}$ is satisfied throughout the frequency range.

The corrections in the asymptotic curve, as well as the phase of the numerator and denominator, are designated as (1) and (2), respectively. The amplitude and phase of Z_2'' and the calculated transfer coefficient are shown by the solid lines in Fig. 4.

As Fig. 4 shows, the transfer coefficients differ insignificantly in the last two cases. The analytical expressions for the functions of Z_2' and Z_2'' can easily be written as follows:

$$Z_2' = \frac{3{,}09}{\frac{1}{6}p+1}; \quad Z_2'' = \frac{2{,}82\left(\frac{1}{6}p+1\right)}{\left(\frac{1}{5}p\right)^2+2\cdot 0{,}71\frac{1}{5}p+1}.$$

Conclusions

1. This method makes it possible to calculate the parameters of a matching quadrupole for passive loads of any complexity with both lumped and distributed parameters. The necessary information on the load is limited to the value of the frequency dependence of its impedance in the matching band.

2. This method eliminates the need for using the Chebyshev or Butterworth polynomials to approximate the power transmission coefficient, which makes it possible to obtain good agreement at low

orders of $Z_2(p)$, i.e., with a small number of elements of the matching quadrupole.

3. The curves given in Figures 2-3 in this report are sufficient for the calculation.

APPENDIX

Conditions of Physical Realizability of Z_2

As we noted above, function $Z_2(p)$ should be a PRF. The necessary and sufficient conditions of the positiveness and reality of rational function $Z(p)$ are [8]:

1) the function is real at real values of the variable $p = \sigma$; 2) at $p = i\omega$ there is a nonnegative real part; 3) there are no poles in the right half-plane of the complex variable; 4) there are only simple poles with real positive remainders on axis $p = i\omega$.

The sufficient conditions of positiveness and reality are

established in the theorem below based on these generally-accepted conditions. These conditions are convenient if the analytical expression of the function is found from the logarithmic characteristics.

Theorem. Let function Z(p) be repesented by the product of factors T, $(Tp)^{\pm 1}$, $(Tp+1)^{\pm 1}$, $(T^2p^2+2\xi Tp+1)^{\pm 1}$ (T, ξ are real positive numbers, $0 \leqslant \xi < 1$). If we designate $Z(i\omega)=|Z(i\omega)|e^{i\varphi}$ at p = iω and φ satisfies inequalities $-\frac{\pi}{2}<\varphi<\frac{\pi}{2}$, then Z(p) is a PRF.

Proof. We will show that if the conditions of the theorem are satisfied, the necessary and sufficient conditions of the positiveness and reality of the functions cited above are satisfied.

1. At real values of the variable p = σ, function Z(p) is real, since all coefficients T and ξ are real numbers.

2. The real part of $Z(i\omega)$ is nonnegative on axis p = iω. It is determined by the following expression:

$$\operatorname{Re} Z(i\omega)=|Z(i\omega)|\cos\varphi.$$

According to the condition of the theorem $-\frac{\pi}{2}<\varphi<\frac{\pi}{2}$; therefore, $\operatorname{Re}Z(i\omega) \geqslant 0$.

3. Z(p) does not have poles on the right side of the complex plane. Actually, from the condition of the theorem $T > 0$, $\varepsilon \geqslant 0$; therefore, the zeroes and poles in Z(p) will only be located on the left side of the half-plane or on axis $i\omega$.

4. Poles Z(p) on axis $i\omega$ should be simple with real and positive remainders.

Suppose that at point $p = i\omega_0$ function Z(p) has pole n of series ($n \neq 1$). Then the expansion of Z(p) into the Laurent series relative to point $i\omega_0$ will be [8]:

$$Z(p)=\frac{a_{-n}}{(p-i\omega_0)^n}+\dots+\frac{a_{-1}}{p-i\omega_0}+a_0+\dots$$

We will draw a circle with its center at point $p = i\omega_0$ and a radius as conveniently small as possible, but not equal to zero. We will designate:

$$p-i\omega_0=\rho e^{i\theta},$$
$$a_{-n}=A_{-n}e^{i\psi}.$$

At $p\to i\omega_0$, disregarding all the terms of the series except the first on the circumference of radius ρ, we will have

$$Z(p)=\frac{A_{-n}}{\rho^n}e^{i(\psi-n\theta)}.$$

Moving over the circumference, we will intersect axis $i\omega$ twice: above point $i\omega_0$ - at point $i\omega_1$, where $\theta_1 = \pi/2$, and below $i\omega_0$ - at point $i\omega_2$, where $\theta_2 = \pi/2$.

From the condition of the theorem, angles $\varphi_1 = \Psi - n\theta_1$ and $\varphi_2 = \Psi - n\theta_2$ at Ψ = const should satisfy the inequalities:

$$-\frac{\pi}{2} < \Psi - n\frac{\pi}{2} < \frac{\pi}{2}, \quad (1)$$

$$-\frac{\pi}{2} < \Psi + n\frac{\pi}{2} < \frac{\pi}{2}. \quad (2)$$

We will assume that $\Psi > 0$; then (2) is not satisfied at any $n \geqslant 1$. If $\Psi < 0$, (1) is not satisfied at any $n \geqslant 1$. Therefore, it is necessary to set = 0; then we will obtain n = 1 from (1) and (2).

Thus, the pole at point $i\omega_0$ is simple (n = 1), and coefficient a_{-1} is the remainder of $Z(p)$ in this pole, whereupon the remainder is real and positive ($\Psi = 0$).

The sufficiency of the conditions of the theorem to make function Z(p) a PRF has been proven. The need for these conditions was shown in the introduction.

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Fig. 1. General broad-band matching circuit.

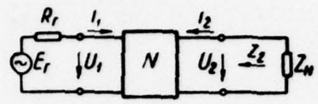


Fig. 2. Curves of dependence $\varphi_H(\varphi_2)$ for different values of ε and G

(— G = 0.6; - - - G = 0.8; -.-.- G = 1).

KEY: (1) dB.

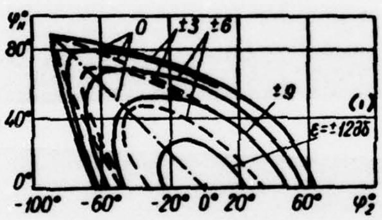


Fig. 3. Logarithmic characteristics of function: - - - $(Ti\omega+1)^{-1}$ and ——— $[(Ti\omega)^2+2\xi Ti\omega+1]^{-1}$.

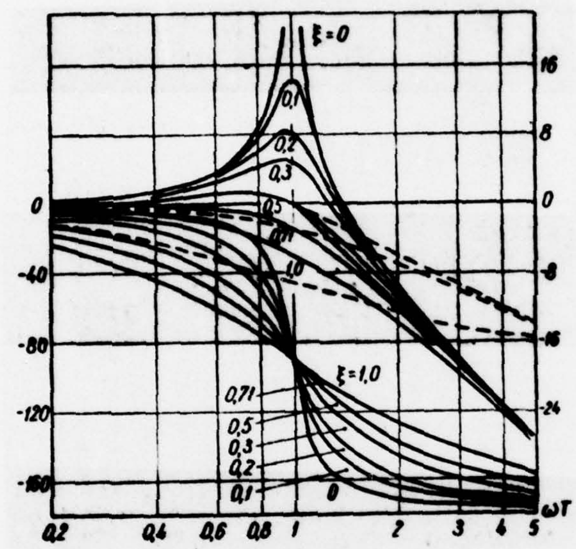
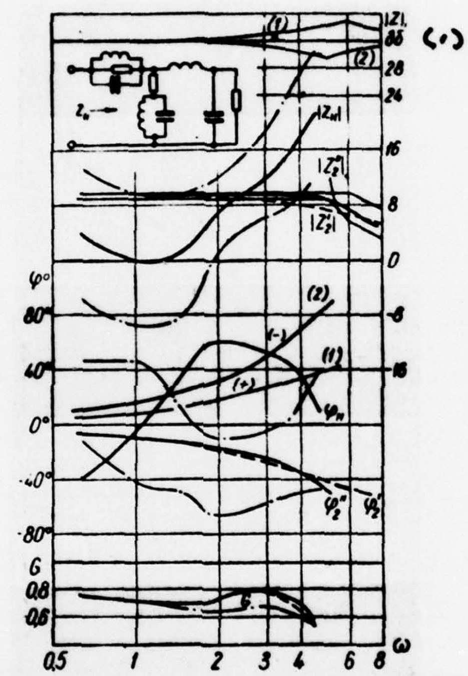


Fig. 4. Diagram of load and its normalized impedance (---- module, phase and frequency dependence of transfer coefficient Z_2'; - module, phase and calculated transfer coefficient of Z_2'').

KEY: (1) dB.



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A210	DMAAC	2
B344	DIA/RDS-3C	8
C043	USAMIIA	1
C509	BALLISTIC RES LABS	1
C510	AIR MOBILITY R&D LAB/FIO	1
C513	PICATINNY ARSENAL	1
C535	AVIATION SYS COMD	1
C557	USAIIC	1
C591	FSTC	5
C619	MIA REDSTONE	1
D008	NISC	1
H300	USAICE (USAREUR)	1
P005	ERDA	1
P055	CIA/CRS/ADD/SD	1
NAVORDSTA (50L)		1
NASA/KSI		1
AFIT/LD		1

ORGANIZATION		MICROFICHE
E053	AF/INAKA	1
E017	AF/ RDXTR-W	1
E404	AEDC	1
E408	AFWL	1
E410	ADTC	1
E413	ESD	2
	FTD	
	CCN	1
	ETID	1
	NIA/PHS	1
	NICD	5